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Architecture and Experimental Results for Quality of Service in Mobile Networks using RSVP and CBQ

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Efforts are underway to enhance the Internet with Quality of Service (QoS) capabilities for transporting real-time data. The issue of wireless networks and mobile hosts being able to support applications that require QoS has become very significant. The ReSerVation Protocol (RSVP) provides a signaling mechanism for end-to-end QoS negotiation. RSVP has been designed to work with wired networks. To make RSVP suitable for wireless networks, changes need to be made by: (i) changing the way control messages are sent, and (ii) introducing wireless/mobile specific QoS parameters that take into account the major features of wireless networks namely high losses, low bandwidth, power constraints and mobility. In this paper, an architecture with a modified RSVP protocol that helps provide QoS support for mobile hosts is presented. The modified RSVP protocol has been implemented in an experimental wireless and mobile testbed to study the feasibility and performance of our approach. Class Based Queueing (CBQ) which is used as the underlying bandwidth enforcing mechanism is also modified to fit our approach. The experimental results show that the modified RSVP and CBQ help in satisfying resource requests for mobile hosts, after handoff occurs. The experiments also show how different power and loss profile mechanisms can be used with our framework. The system performance using the modified RSVP control mechanism is also studied.

Keywords: Wireless Networks, Mobility, Quality of Service, ReSerVation Protocol, RSVP, Class Based Queueing

1. Introduction

It will be desirable in future wireless and mobile communication networks to provide resource allocation for the various classes of applications that require Quality of Service (QoS) support. A big drop in service quality when a call handoff is made as the mobile moves from one region to another may not be acceptable for these applications. It is

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therefore required to maintain the QoS of these applications, in the presence of user mobility with the use of resource reservation.

QoS support in wireless networks has been attempted at various levels in the protocol hierarchy. Various MAC level protocols have been suggested for achieving QoS in wireless networks [1–3] aided by a large number of scheduling algorithms [4–6]. Many of the MAC based algorithms that have been proposed use a centralized channel allocation scheme with the help of a base station and follow a rigid temporal structure which makes practical implementation complex. There are many QoS/fair scheduling approaches where in all the scheduling activity is logically done at the base station which makes QoS guarantees in the downlink direction possible [5–7]. Reservation protocol based approaches to guarantee QoS have also been suggested [8, 9]. An enhanced Class Based Queueing (CBQ) approach presented in [10] takes into account the channel state of the wireless link before scheduling packets on the link. The BARWAN (Bay Area Research Wireless Access Network) [11] project studies overlaid wireless networks of varying bandwidth and latencies to provide connectivity to mobile hosts. Routing and resource allocation decisions are moved to local subnets and multicasting is used to send packets to likely adjacent cells to reduce latency. The system does not address resource reservation however. The Mobiware project [12] discusses the use of Mobile IP and RSVP for QoS guarantees with an experimental testbed underway. Mobiware provides a QoS-aware middleware for multimedia communications. The Dataman project [8,13] considers using RSVP for mobile networks. One of the drawbacks of this architecture is that a mobile is assumed to have a prior knowledge of its mobility. The architecture also uses Mobile IP for routing. A micro-cellular architecture was proposed in [9] where advance passive reservations [8] helped reserve resources in a mobile environment.

In this paper a modified RSVP/CBQ mechanism is proposed which takes into account these major features of a wireless/mobile network. We have chosen RSVP as the QoS signaling mechanism since it has been actively considered for the wired Internet. However, the paper does not claim that RSVP is the most appropriate mechanism for resource request signaling in wireless networks. Similarly, CBQ has been chosen as one specific scheduling mechanism. A number of other scheduling mechanisms, such as those listed earlier, can also be used in conjunction with RSVP.

In the network architecture considered, a mobile in a region is served by a base station which is connected to the wired network. Resource reservations are made using RSVP and CBQ between the base station and the mobile. To make sure that a mobile has reservations guaranteed as it moves from one region to another, base stations make reservations with other base stations in all the neighboring regions. These reservations will remain “passive” [8]. That is, the resources may be used by other mobiles until it is needed for this particular mobile. This ensures that resources are not needlessly tied up for potential incoming mobile hosts. The neighboring base stations are made aware of the mobiles' potential resource requests. When the mobile does move into the neighboring base station's coverage area, the passive reservations are made active and the mobile is provided the requested resources.

The Integrated Services (Intserv) architecture and RSVP (ReSerVation Protocol) signaling protocol [14,15] enable applications to signal per-flow requirements to the network. Intserv parameters are used to quantify these requirements for the purpose of admission control. RSVP provides a signaling mechanism and guarantees must be provided by underlying scheduling mechanisms like CBQ. RSVP has been designed to work in the wired networks. To tailor RSVP to work with wireless networks, the major characteristics of wireless networks must be considered. The scheduling mechanism must also be altered to take into account all the signaling changes made to RSVP.

The work presented in this paper takes into account all the major features of wireless networks namely: (i) high losses, (ii) low bandwidth, (iii) battery power constraints and (iv) mobility. The original contributions of this paper are summarized as follows: (1) an architecture is provided to extend the use of RSVP and CBQ for wireless networks. The architecture provides support for making advanced resource reservation during mobility; (2) hooks to support various wireless specific QoS parameters are provided. The RSVP signaling messages have been enhanced to carry these wireless specific QoS parameters; (3) the underlying scheduling program, CBQ, is modified to use the parameters signaled by RSVP and change its scheduling or packet drop policy accordingly; and (4) the architecture has been implemented on an experimental testbed and the software can be used to provide necessary QoS support for various applications. Our goal was to develop an implementation that can potentially be used by other researchers for incorporating other QoS mechanisms in wireless networks for experimental study.

The results from our experimental work are summarized here. The modification of RSVP and CBQ to experimentally substantiate the architecture is presented. QoS parameters specific to the mobile environment – loss profiles, probability of seamless communication, performance feedback factor, power level, power profile and rate reduction factor are considered and described in detail later. The results show: (i) the establishment of a passive reservation that is later converted to active reservation after handoff, (ii) the utilization of passively reserved bandwidth for current applications in a cell, (iii) the incorporation and usage of loss profiles, power profiles, power level and performance feedback and (iv) modifications of the RSVP control message mechanism.

The rest of the paper is organized as follows. Section 2 provides an outline of the architecture. An overview of RSVP and CBQ, used for traffic classification and scheduling, is given in Section 3. Details of the various wireless/mobility specific QoS parameters along with changes that need to be made for RSVP and CBQ are also discussed. Section 4 discusses our experimental testbed. Experimental results are discussed in section 5 followed by conclusions in section 6.

2. Proposed mobile-RSVP mechanism

This paper assumes a micro-cellular network architecture, with a geographical region divided into cells. Each cell has a Base Station (BS) serving all mobiles within its coverage region and is connected to the wired network. When a mobile moves to another cell, it is handed off to the base station serving that cell.

Quality of Service guarantees in mobile networks requires some form of resource reservation as the mobile moves between regions. Resource reservation in a mobile environment is a challenge since reservations have to be maintained wherever the mobile goes. Typically there may not be prior knowledge of the future location of the mobile. The sender or receiver of an application can be a mobile, the base station or any host on a wired network. In the discussion here, the communication between the base station and the mobile is emphasized. One way of guaranteeing QoS, as a mobile moves from one cell to another, is to reserve resources with the base stations in all the neighboring cells because the mobile might move into one of them. This would be a waste of limited wireless resources. Therefore, we allow use of these reservations by other mobiles in the cell till the mobile in question moves into that cell. These reservations made in the neighboring cells will be thus "passive" and can be used for other applications till the mobile actively starts using them [8]. The "passive" reservation not only guarantees the mobile the required bandwidth when it moves to another region, but also ensures that the resources are not wasted until the mobile starts using it.

The concept of passive reservations is better explained as an "Advanced Reservation Signaling" mechanism. We use the term passive reservations to be consistent with the original idea proposed in [8]. Each base station can potentially reserve a fraction of the cell bandwidth – handoff bandwidth – for incoming handoff mobiles (this concept is already used in cellular networks). The remaining bandwidth – local bandwidth – will be to allocated to mobiles currently in the cell. Different techniques for determining this allocation are studied in [16]. The passive reservation mechanism thus reserves a portion of this handoff bandwidth for a given request.

For efficiency reasons, this passive reservation at a neighboring base station should expire after a period of time. This will require base stations to periodically send refresh messages for passive reservation requests. Also, if the bandwidth needed for mobiles already in the cell exceeds the local bandwidth, then the system can temporarily let the local mobiles use some of the handoff bandwidth. This sharing is a design decision and a system administrator can choose to either allow or disallow this.

Below, we use an example to illustrate the passive reservation concept.

2.1. Passive/Active Reservations Example

Fig. 1 aids the discussion in this section. A, B, C, etc denote the cells. BS represents the base station and M represents the mobile. The solid line represents an active reservation while the dotted line indicates a passive reservation. We assume that a base station knows the addresses of the base stations in all the neighboring cells.

In a wireless environment there is a need to distinguish between the two kinds of reservations that need to be made: a) between the sender and various base stations in neighboring cells in the wired network, and b) between the base station and the mobile in the wireless region. In our example, the mobile M is initially in cell A. BSa is the base station in this cell and resource reservations must be made between BSa and M. When the mobile moves, it could move into any of the other six cells. At this point we will need to make two kinds of resource reservations that are "passive": a) between the "current" base station BSa and all other base stations namely BSb, BSc, BSd, BSe, BSf and BSg, and b) base stations BSb, BSc etc. make a passive resource reservation on their wireless interfaces to accommodate mobile M's potential requests. In the example provided above, the base stations are assumed as the end points of an application. This need not be the case. If another host is the end-point, a reservation needs to be made between that host and the base station in the wired domain.

In fig. 1(b) we see that the mobile M has moved into cell F. At this point the resources that were labeled passive in the wired environment between BSa and BSf are made active and the resources on the wireless interface of BSf is activated to be used for communication between BSf and M. All other resources reserved passively can be deleted now. This scenario further continues as shown in figures 1(c) and (d). At some point, we could make a re-routing decision so that the sender BS directly connects to the BS in a cell where a mobile is currently located instead of going through all the intermediate BSs. This decision will be a trade-off between the re-routing cost and the cost of reserving resources in all the intermediate BSs. More information on the re-routing decisions is beyond the scope of this paper and can be found in [17].

In our network architecture, RSVP is used as the signaling mechanism for resource reservation along with Class Based Queueing (CBQ) as the underlying scheduling mechanism. We are aware that there are concerns about RSVP, namely scalability and the inability of some applications to express the QoS requirements using the Intserv model. Presently, there is interest in development of Differentiated services (Diffserv or DS) [18, 19]. In contrast to RSVP's per-flow orientation, Diffserv networks classify packets to one of a small number of aggregated flows, based on the setting of bits in the TOS field of each packet's IP header. We have reported studies on the feasibility of using Diffserv for wireless networks in [20].

The passive reservation scheme discussed in this section brings up the issue of routing in the architecture. A brief description of the routing mechanism is described next.

2.2. Routing Support

The routing scheme is strongly tied to the QoS architecture. In other words, during route computation we need to make sure that the paths on which the data will be sent have resources reserved for the application. In a way, the problem can be looked upon as a form of QoS routing. Mobile IP [21] is a recently proposed standard for routing in mobile networks which uses the concept of a home agent (HA) to keep track of the current location of a mobile. Mobile IP is not designed to support frequent mobility and is suited for long-term mobility since all route updates need to be made at the home agent (HA).

One possible solution to the latency issues involved with Mobile IP is to use a mechanism that does not contact the HA at every move. This can be done by reflecting the current location of the mobile using route table updates. Though this is a faster solution for continuous mobility, it is not a scalable approach since the routing table size can grow to be very big with increasing number of mobiles. In the proposed mechanism the architecture is divided into "*routing-domains*" with different routing policies for intra-domain and inter-domain mobility. Intra-domain mobility uses address table change and proxy ARP take care of routing. Mobility between domains is aided by Mobile IP for routing. More details about the routing architecture can be found in [17].

In this section, the working of the mechanism of passive reservation in the proposed architecture was discussed. A brief description of the routing protocol was also given.

3. Enhancement of RSVP and CBQ for Wireless/Mobile Networks

This section provides an overview of RSVP and CBQ mechanisms which are used for resource reservation in the proposed architecture. Modifications made to RSVP and CBQ to make it suitable for wireless networks are also discussed.

3.1. An Overview of RSVP and CBQ

The current Internet architecture with the best-effort service model is inadequate for new classes of applications that need QoS. For a network to deliver appropriate QoS we need a mechanism to manage network resources. Integrated services approach helps quantify and satisfy the needs of QoS-enabled applications. The RSVP protocol [14] is a network management setup protocol designed to communicate requests among participating entities. RSVP uses receiver initiated reservation requests conforming to the Integrated Services flow specifications [22] to help applications reserve resources.

After a high-level dialogue, the initiator of a flow that wants to use RSVP generates PATH messages to each accepting receiver. The PATH message is routed to the receiver(s) using the routing algorithm(s) used by the underlying network layer. The receiving host(s) then makes resource reservation requests using RESV messages sent in the reverse path to the sender. The mechanism works as follows: The PATH message contains the specifications of the application that will use this reservation. The receiver receives this PATH message and sends RESV message towards the sender specifying the flow it wants to receive. As the RESV message flows back to the sender, reservations are made along the way. If at any point along the path the request cannot be supported, that request is blocked. Otherwise, this request is merged with other requests to the same sender in order to share the bandwidth in a better way.

RSVP is thus a signaling mechanism to carry the QoS parameters from the sender to the receiver and to make reservations along the path. These reservations must be satisfied at the hosts and routers by some kind of traffic scheduling mechanism. In the wireless environment, the wireless link is shared among the mobiles in uplink and downlink directions. Therefore, a link-sharing mechanism that meets resource requests of the mobiles (and their connections) is required. The Class Based Queueing (CBQ) [23] mechanism was designed to provide link-sharing. The control of limited Internet resources involves local decisions on usage as well as considerations for end-to-end requirements. Link sharing mechanisms allow gateways to distribute bandwidth probably among various agencies or protocol families or traffic types. Each node (host or routers) that is capable of QoS control needs a packet scheduler and a classifier, which is handled by CBQ mechanisms. It consists of: (i) a *Classifier*, which classifies packets into a pre-defined class, (ii) an *Estimator*, which estimates bandwidth usage of each class and (iii) a *Packet scheduler*, which selects the next class to send a packet.

3.2. Basic Modifications to RSVP and CBQ

In this section, the major modifications needed for using RSVP and CBQ in a wireless environment are discussed. Flow of signaling messages during mobility is discussed.

3.2.1. Reserving Resources Under Mobility

Using RSVP and CBQ to reserve resources is discussed using fig. 2 with two neighboring cells. The base station (BS) is considered as the sender of an application for simplicity. We use the RSVP protocol, modified to recognize passive and active reservations. In fig. 2(a), the mobile is shown to be in Cell 1 in which the sender/BS also resides. The BS sends PATH messages to the mobile and since the reservations are going to be used, it is indicated as an active reservation denoted as [1] in Fig. 2(a). The mobile responds with an active RESV message if it can accept the call (shown as [2] in fig 2(a)).

After this point, the sender of the application has made sure that resources are reserved for this application. The BS now has to make passive reservations with the BS in Cell 2. The traffic specifications of this passive reservation are the same as those used by the active reservation. In fig. 2(a) the "current" BS 1 sends PATH messages denoting it is a passive reservation to BS 2 (shown as [3] in fig. 2(a)) and then BS 2 sends a "passive" RESV message to BS 1 (shown as [4] in fig. 2(a)). BS 2 also makes reservations on the wireless interface (shown as [5] in fig. 2(a)) for the wireless link which the mobile may use. (This reservation is done by CBQ by creating a class for the mobile (i.e. filter specifies the mobile) using the special bandwidth reserved for mobile classes. RSVP signaling cannot be done as yet because the mobile is not yet in Cell 2).

Once the mobile has moved to the neighboring cell 2, the mobile and the base stations BS 1 and BS 2 will know that a handoff has been made. At this point, PATH and RESV messages denoting an active reservation are exchanged between BS 1 and BS 2 and between BS 2 and the mobile as shown in fig. 2(b). Reservation between BS 1 and the mobile can be deleted by sending a TEAR message or by just letting the reservation be deleted by the lack of refreshing PATH and RESV messages.

3.3. Overhead of RSVP Control Messages

One of the major concerns with soft-state protocols is scalability. Many RSVP flows across the wireless link can cause a lot of control information to flow across the wireless link. This can consume a substantial portion of the limited wireless bandwidth. It is necessary to consider ways to reduce the amount of control information, when possible.

The RSVP control messages can be differentiated as: (i) trigger messages that are sent to establish connections and (ii) refresh messages that are used to maintain the state along the path. In our architecture, passive reservation requires that PATH and RESV messages be sent between the current base station and the set of possible future base stations. To reduce the problem of having a lot of control messages, we follow the approach of sending only trigger messages for passive reservation. No refresh messages are sent to confirm the reservation. Once the mobile has moved into the region of another base station, explicit TEAR messages are sent to delete all the other passive reservations.

3.4. Other Modifications to RSVP and CBQ: Wireless/Mobile QoS Parameters

QoS parameters for real-time services include parameters like packet delay, packet loss rate, delay jitter and minimum and maximum bandwidth. These parameters are specified and handled by Integrated Service classes supported by RSVP and CBQ. Integrated Services offers QoS based on three service classes: *Guaranteed Service* which provides a firm bound on data throughput and delay along the path, *Controlled Load Service* where probabilistic promises are made to provide some service and *Best Effort*

Service with no performance guarantees. Applications using Integrated Services Specification are characterized by traffic and flow specifications (Tspec and Flowspec [15]) with parameters including token bucket rate, token bucket depth, peak data rate, minimum policed unit and the maximum packet size. Apart from the above mentioned QoS parameters, there are certain parameters that will help deal with problems which are unique to a mobile computing environment. They are enumerated below based on the various characteristics of wireless networks. For each characteristic, we have described the changes we designed and implemented to RSVP and CBQ.

3.4.1. Mobility

Mobile networks have the problem of possible blackout situations during handoffs. Also, reservations in a mobile environment must be done in advance (passive reservations) to get as much resources as possible. *Probability of seamless communication* and *Rate reduction factor* deal with the mobility aspect. *Probability of seamless communication* [24] defines the nature of breaks that can be allowed in the service. In essence, the probability of seamless communication defines how "seamless" the fade should seem to the application. *Rate reduction factor* deals with the proposed passive reservations. Since a BS has to make passive reservations in advance with all the neighboring BSs, there is a possibility that some of these reservations would be turned down because of lack of resources. A parameter denoting a factor by which the original resource request can be reduced in case a reservation does not go through is useful. This is similar to re-negotiation or degradation which has been studied earlier. Such a mechanism will ensure that at least some resources are reserved.

RSVP: RSVP signaling messages have been modified to carry the rate reduction factor and probability of seamless communication parameters. If reservation fails, the end systems re-negotiate by sending new RSVP control messages based on the rate reduction factor parameter. Details of using RSVP for passive reservations is discussed in section 3.2.

CBQ: CBQ mechanisms handle the job of scheduling packets based on the bandwidth requirements of a particular class of applications. The bandwidth that has been reserved but not used for a given class must not be wasted. It is necessary to have a mechanism that lets the resources be used by other applications till the intended application wants to use it. Fortunately, this is supported by CBQ. The CBQ mechanism allows a class of applications to borrow bandwidth from another class if the present class is going over its allocated bandwidth and also if the other class is identified as a borrowable class. Therefore a passive reservation can be identified as a class from which other classes can borrow bandwidth.

3.4.2. Losses in Wireless Networks

Packet loss in a mobile environment is an important issue to consider because of the limited bandwidth of a wireless network and the possible blackout situations during mobility. The QoS parameter *loss profiles* [24] gives applications an opportunity to choose between a bursty loss or a distributed loss in case of an overloaded situation. For example, an audio application may choose a bursty loss while a video application may perform better with distributed losses. A lossy channel may also prevent a mobile from receiving/sending the required amount of data. For example, a base station may be sending data to the receiver based on some rate agreement. The mobile may not receive this data because of a lossy channel. *Performance feedback factor* is introduced for the mobile to convey (to the BS) the data it is receiving so that the required compensation can be provided [5,6].

RSVP: Apart from the parameters that help data traffic, some modifications need to be made for RSVP control messages too. PATH and RESV messages can be lost because they are sent as unreliable datagrams. The loss of PATH and RESV trigger messages can cause reservation setup to be delayed by upto 30 seconds when the next refresh interval is scheduled [15] resulting in unacceptable quality of service during this period. Staged refresh timers have been suggested in [25,26] for this problem. The approach we follow is: trigger messages are sent until (i) a RESV message is received or (ii) a limit on number of messages is reached. The idea being that, if the channel is good, (i) one of the intended messages will reach the destination and (ii) additional messages can be treated as refresh messages.

CBQ: Currently, when incoming packets exceed the capacity of the network, CBQ uses the tail dropping technique to drop the packets. CBQ must be modified to accommodate the loss profiles parameter. CBQ either drops the packets in bursts or schedules a distributed loss.

3.4.3. Power Restrictions

Mobile systems have power limitations that must be considered in protocol and application design. The base station needs to be aware of the power status of the mobile so that it can adapt sending data to the mobile. A *power level* parameter is sent along with the control messages from the mobile indicating the percentage of battery power that is left. Based on the the power level, various applications would like to react in different ways. For example, some applications would like to reduce the average rate of sending data while others may choose to send some important packets while dropping others as in layered video. The behavior of the applications during various power levels is characterized with the *power profile* parameter. Applications may use the power level and the power profile to tailor their behavior.

RSVP: The network interfaces in mobiles consume significant amounts of battery power

[27]. Reducing unnecessary refresh messages will help in power reduction. Since there is a single hop from the base station to the mobile, there is no possibility of a route change between the base station and the mobile and therefore refresh messages can be sent only from the mobile to the base station. Also a single refresh message is sent from the mobile to refresh the state of all sessions. This reduces the number of outgoing packets thereby reducing power spent.

CBQ: CBQ is also modified to use the power level information from the mobile to schedule packets. Scheduling of packets is done based on the power profiles parameter similar to mechanisms described in [28].

Summarizing, the QoS specifications that are supplemented for a mobile environment include: loss profiles, performance feedback factor, probability of seamless communication, rate reduction factor, power level and power profile. Fig. 3 gives an outline of the modifications made at the various protocols layers to support the proposed RSVP/CBQ mechanism. The shaded boxes indicate the layers where the architecture discussed in this paper is implemented. "RSVP+" and "CBQ+" refer to the modified RSVP and CBQ respectively.

What differentiates our work from [8] is the: (i) implementation of various mobile-specific QoS parameters with the RSVP/CBQ mechanism which are discussed below, (ii) use of an experimental testbed to validate the architecture and test the passive reservation mechanism, and (iii) tailoring the RSVP control messages to suit wireless networks. Note that our architecture and implementation provides the necessary hooks for incorporating various QoS parameters. For each of these QoS parameters, many mechanisms to handle the QoS requirements are possible. These mechanisms may be implemented on top of our implementation to obtain realistic experimental results.

4. Experimental Testbed Implementation

In this section, details of the experimental testbed are provided. The modifications that are made to RSVP and CBQ to make it suitable for wireless/mobile networks are also discussed.

4.1. The Testbed

An experimental testbed to test our proposed architecture has three Pentium systems that operate as base stations. Each base station is equipped with an Ethernet card and a 2.4GHz WaveLAN ISA card. The base stations are in adjacent cells and the different Network Identifiers (NwID) of the WaveLAN cards identify the cells. The testbed also has two mobiles which are equipped with 2.4GHz PCMCIA WaveLAN cards. All the systems run FreeBSD 2.2.2. The testbed uses RSVP code version 4.2a2 [29] and alternate queueing package version 0.4.2 [30]. The testbed also uses:

- FreeBSD WaveLAN driver for PCMCIA cards which supports roaming [31]. The WaveLAN ISA driver has been modified to produce link level beacons. The beaconing systems help in identifying a particular cell. The mobile uses the NwID of the beacon signal to identify the base station it is attached to. The signal strength of the beacon helps determine when a mobile is moving from one cell to another. (The source code for the beacon generator can be obtained at [32]). The driver from [31] has also been modified to (i) use 2.4GHz cards, (ii) use CBQ and (iii) work with our modified WaveLAN ISA driver beaconing system.
- "Modified" RSVP that: (i) carries mobile specific QoS parameters (described in section 3.4) along with the regular QoS parameters, (ii) is aware of passive reservations, (iii) has timing details for control messages that are changed to take care of bandwidth and power constraint problems and (iv) is modified to make sure that the right flow will use the passive reservation.
- "Modified" CBQ that: (i) is aware of the nature of packet drops needed for the application (loss profiles parameter) from the RSVP signaling and drops arriving packets based on this parameter. Packets at the queue are either dropped in bursts or in a distributed manner, (ii) is "intelligent" to send packets based on power level. The scheduling is modified based on the power profiles parameter specified during RSVP signaling and (iii) modifies the scheduling based on the compensation bandwidth specified using the performance feedback parameter.
- Applications used to test our architecture: A few applications are modified/written to use RSVP API (RAPI) interface of RSVP to help these applications request resources. These are: (i) A traffic generator program that uses UDP or TCP to dump packets on the network at a given rate. (ii) H.263 video compression [33] simulation model with encoder and decoder from Telenor networks [34]. The package has some video streams that are encoded using the H.263 format. The decoder in this package was modified to accept video packets over the network and also to use RSVP API to reserve resources. (iii) The benchmarking program Netperf [35] has been modified to use RAPI interface to reserve resources.
- Other tools to test the architecture include Advanced Power Management (apm) tool for monitoring the battery power level in laptops [36].

4.2. Details of Modifications to RSVP

In this section the modifications that are made to RSVP are discussed. The merging of the various QoS parameters are described initially. The modification of RSVP for passive reservations is also discussed.

Merging of QoS parameters: All the mobility QoS parameters, namely loss profiles, probability of seamless communication, performance feedback factor, power level, power profiles and rate reduction factor, are incorporated into the RSVP signaling messages.

Merging of the various mobile specification parameters must be done along with the traffic and flow specifications. A discussion of how traffic and flow specs are merged is provided in [15], [37] and [38]. In RSVP, a reservation request has a set of options which are collectively called a reservation style. One reservation option is concerned with the way reservations are done for different senders within the same session – a "distinct" reservation for each sender or a single reservation that is "shared" among all packets of selected senders. Another reservation option controls the selection of senders – an "explicit" list of senders or a "wildcard" that implicitly selects all the senders to the session. The styles that are defined are: (i) Wildcard filter: A single shared reservation into which flows from all upstream senders are mixed, (ii) Fixed filter (FF): A distinct reservation with explicit sender selection and (iii) Shared Explicit: A reservation style where receivers choose senders but reservation is shared.

The parameters are merged as follows: (i) *Loss profiles*: This parameter depends on the nature of the application and is not affected by the reservation style. (ii) *Probability of Seamless Communication*: When using a wildcard filter the LUB (Least Upper Bound)[1] of the parameter is chosen. Larger values indicate that the mobility must be as seamless as possible. While using a fixed filter reservation, this parameter is sent up towards the sender since each reservation is distinct. In case many receivers request data from the same sender, the largest of this parameter is sent towards the sender. Shared explicit reservation style also sends the "largest" value towards the sender. (iii) *Rate Reduction factor*: When using a wildcard filter, the GLB (Greatest Lower Bound) of this parameter is sent up while merging parameters. A smaller reduction factor value indicates that we want to make a reservation as close to the original request as possible. Fixed filter reservation with one sender and many receivers and the shared explicit filter style send up the smallest value of this parameter during merging. and (iv) *Power Level, Power Profiles and Rate Feedback Factor*: These parameters make sense only between the base station and the mobile. Therefore the parameters need not be merged and the reservation style does not affect them.

Introduction of Passive Reservation: Active reservation is made between a sender and a receiver (say a wired host and a mobile respectively). Passive reservations are made

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[1] A "least upper bound" (LUB) returns a parameter at least as large as any of the parameters being merged while a "greatest lower bound" (GLB) returns a parameter at least as low.

between the base stations and they may be used later by the sender and the receiver. Therefore while making passive reservations, the base stations act as originators of the RSVP PATH and RESV messages on behalf of the sender and receiver. The modification of RSVP to include both the addresses is shown in fig. 4. When a reservation is labeled passive, the sender and receivers are identified as the base stations (fig. 4(a)). When the reservation is active, the original senders and receivers use the reservation (fig. 4(b)). The extra addresses should not produce too much traffic since refresh messages for passive reservation are not sent.

4.3. Details of Modification of CBQ

Loss profiles is guaranteed by changing the way packet dropping is done at the queues by CBQ. With distributed loss, if a packet arrives at a full queue, a packet is removed from the middle of the queue and the currently arrived packet is queued. When a packet arrives at a full queue for bursty loss, the arriving packet along with a few packets at the end of the queue (based on the burst depth) are dropped. The value of the burst depth is signaled by the sender based on the nature of application. The power profiles parameter is set in CBQ when the signaling is done. The power profile defines the nature of scheduling. Whenever the power level messages arrive CBQ modifies its scheduling mechanism based on the power profile value. For example, for layered video application, only the base layer video is sent. The rate feedback factor is also sent along with the PATH/RESV messages to alter the scheduling of packets at the base station.

4.4. The Handoff Mechanism

The WaveLAN driver at the base station has been modified to produce link level beacons. These beacons are used by a mobile to find out the base station in a cell. The handoff mechanism is shown in fig. 5. The figure shows a time-line of activities at the mobile (with *t4* being with most recent activity). Initially the mobile is in the region of the "Old basestation" and is receiving beacons from this base station (shown as *t1*). As the mobile moves, it receives a stronger beacon from another base station which is called the "New basestation" (represented as *t2*). The mobile now signs off from the "Old basestation" (shown as *t3*) and registers with the "New basestation" (shown as *t4*). The average handoff time (from 15 trials), which is the latency from when the signon message is sent to the time the first data packet arrives, is 90msecs.

5. Experimental Results

In this section the experimental results from tests conducted on the testbed are presented. The basic aim of the experiments are to show:

- The modified resource signaling mechanism works correctly – more specifically, we show that we can make passive reservations, schedule based on these reservations and show how passive bandwidth can be used by other programs till needed by the session that makes the reservation.
- Wireless-specific QoS signaling modifications to RSVP work correctly. RSVP can signal the wireless QoS parameters and CBQ has been modified to schedule based on these QoS parameters.

The need for reservation in networks is an important issue in itself with many arguments for and against reservations. For example, [39] uses a simple analytical model to address the question: Should the Internet retain its best-effort-only architecture, or should it adopt one that is reservation-capable? Thus we restrain ourselves to a narrower problem of the need for passive reservations. This work is based on the premise that when resource reservations are made in the wired Internet, how can that be extended to the wireless network?

5.1. Experiments on Passive Reservation

In this section, experiments conducted to show that our reservation scheme works correctly and the use of passive bandwidth are also discussed.

Experiments with Video Streams

The first set of experiments to test the architecture was done using the H.263 video streams from [34]. The need for passive reservation is shown here. The experimental testbed has a sender (a wired host), a base station and two mobiles (which are the receivers). Initially video is sent over the wireless link from the sender with no other traffic interference (i.e. there is only one mobile in the cell which is the receiver), which is the ideal case. An average rate of 12.73 frames per second (fps) using the Foreman video stream was recorded as shown in Table 1. Then extraneous traffic (data from a constant bitrate generator and from Netperf benchmarking program) sufficient to load but not overload the wireless link was generated. This extraneous data was sent from the base station to a mobile.

When another mobile moved into the region with passive reservation (of 100Kbps) in place, the average rate of video stream was seen to be around 10.15 fps. Without prior reservation, we observed 3 possible cases: (a) video stream was blocked for several seconds - this may have been caused by either heavy traffic on the link or the loss of signaling messages. Since the applications in the testbed make reservations before sending data, loss of arrival of initial signaling messages can cause reservations to be delayed upto 30 secs [15], (b) the display froze for several seconds while playing possibly because of lack of data which could have been caused by packet losses at the sender, or (c) an average rate of 8.82 fps was observed.

Usage of Unused Passive Bandwidth

This experiment shows the working of passive reservation scheme. The experimental setup consists of three users (User1, User2 and "Mobile") which have reservations respectively for 30%, 22% and 35% of the available bandwidth link estimated to be 1.2Mbps[2] (fig. 6). The experiment was monitored with the help of Tele traffic trapper (ttt) which comes with FreeBSD and the CBQ monitor that comes with the ALTQ package [30] in FreeBSD. (The legends from the output of ttt and CBQ monitor were modified and some traces were removed to increase clarity. This does not affect the results.)

Until approximately 150 seconds, the "Mobile" is not in the region of the BS where the traffic is being monitored and hence does not contribute to the total traffic in the system. Initially User1 and User2 are sending data (from the sender, a wired host, to a single mobile in the region of the BS in question. This mobile is different and not to be confused with the "Mobile" referred to in the figure which moves in after a handoff.) that was reserved for them (shown as (1) in the figure). After that, User1 starts sending more data than what was alloted to it (shown as (2) in the figure). User1 is provided the necessary bandwidth because the reservation made for the "Mobile" is passive and is not yet used by it. We thus see that unused reserved bandwidth is not wasted if another application needs it and hence the term "passive". After a handoff occurs, the "Mobile" moves into the BS's region and the passive reservation is made active (shown as (3) in the figure). Now the "Mobile" starts sending data and so the bandwidth of User1 reduces to its reserved rate (about 30%). User2 is conforming to its reserved rate and hence is not affected (The fluctuations we see at point (3) in the graph may have been caused by some delay in reservation process and data is possibly sent in bursts till it stabilizes. Also, CBQ provides long-term guarantees and there can be some fluctuations in a short-term period.). From this experiment we see that: (i) passive bandwidth is used by other applications if needed, and (ii) when the reservation becomes active, the application that was using this bandwidth has to relinquish it.

5.2. *Experiments with Modified RSVP*

In this section, the working of the various modifications that are made to RSVP are studied. The modifications include changes to the refresh timing of signaling messages and introduction of various mobile specific QoS parameters. The QoS parameters are signaled successfully by RSVP.

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[2] The theoretical bandwidth of WaveLAN cards is 2Mbps. Netperf benchmarking program reports a bandwidth of 1.5Mbps. 1.2Mbps was used so as not to drive the card to its limits.

Losses in the Network Affecting Reservation: In this experiment, the need to send consecutive reservation messages because of the losses in the wireless networks are studied. The experimental set up consists of a base station and a mobile communicating over a wireless link. An error rate of 1% was deliberately introduced into the packets before it was sent on the channel. The time taken for 100 reservation setups was measured. Table 2 shows the time taken when packets were lost and also the average setup time on a good channel. As seen, with losses, regular RSVP required an average time of 29.62 secs while RSVP modified to handle losses requires 1.72 secs.

Effect of RSVP Refresh Messages on Control Traffic: The reduction in data traffic when only the mobile is allowed to send refresh messages is discussed next. PATH and RESV messages are around 200 bytes each. By making only the mobile send the refresh data, the effective control traffic data has been reduced by almost 50%. Allowing the mobile to handle the transmissions will help with the power constraints also. The mobile can periodically choose to turn off its network interface to save power [40]. More information on power constraints follow in section 5.3

Mechanism of the Rate Reduction Factor: The rate reduction factor is used to ensure that at least some resources are available in case passive reservation cannot be made for the entire requested amount of bandwidth. If the network cannot provide the requested bandwidth, a RESV error message is sent to the receiver indicating that the reservation failed during admission control. In this case, the receiver uses the rate reduction factor to reduce the bandwidth specification. As shown in fig. 7, a bandwidth of 80K bytes is available at the interface of the sender. The receiver tries to reserve 90K bytes and gets an admission control error. The reservation rate is reduced by a factor of 0.15 (which is the rate reduction factor) and a RESV message is sent with a rate of 79.5K bytes. Admission control now succeeds and a reservation is made for 79.5K bytes. This experiment demonstrates the re-negotiation capabilities of our implementation.

5.3. Experiments with Modified CBQ

In this section, the various modifications that were made to CBQ are tested in our experimental testbed.

The Loss Profiles Parameter

The loss profiles parameter in a mobile environment defines how a packet drop should be done in lossy situations. An application specifies the kind of loss parameter it wants in the PATH and RESV messages of RSVP. This parameter is conveyed to CBQ that uses it as outlined earlier. Based on the loss profiles parameter the packets are dropped in bursts (the burst depth can be defined by the sender) or in a distributed manner; CBQ uses the tail drop method by default.

The working of the loss profile parameter is shown using an experimental setup which uses Netperf benchmarking [35] modified to use RSVP and sends data from the base station to the mobile. Netperf sends data (TCP in this case) at the maximum rate and is limited by the speed of the link. A maximum CBQ queue length of 10 was chosen for this experiment. The aim of this experiment is to show that the implementation of loss profiles parameter works (What is *not* addressed is: (a) how many packets should be dropped in the distributed approach to make it equivalent to the bursty drop approach? and (b) what is the best scheme of distributed drop we can choose? They are beyond the scope of this paper.). Fig. 8(a) show how the bursty loss mechanism in the testbed works. Every time the queue exceeds the maximum queue length, 5 packets are dropped (this is the burst depth). With distributed loss a single packet is dropped when the maximum queue length is exceeded (fig. 8(b)). It must be noted that since Netperf was sending data at the maximum rate and not a constant rate, a comparison of queue lengths of both methods are not meaningful. The queue length[3] and packets dropped were monitored with the use of *cbqstat* utility which comes along with the ALTQ package [30].

The Power Level and Power Profiles Parameter

Mobile battery power level is an important constraint in wireless networks. Wireless interfaces in computers can be major sources of power drainage if not managed properly [27]. It is therefore advantageous to periodically send the mobile power level to the base station, and let the base station and the mobile adapt the application behavior based on the power profile.

RSVP PATH and RESV messages are used to send power level and power profile parameter. Based on the power profile information and the battery power level, packets are scheduled at the base station (or at the mobile). In our testbed, the sender initially sends the power profile message to the receiver based on the nature of application it is going to send. This power profile information is used by the base station or the mobile while scheduling in a low power situation. We are also considering the possibility of the mobile indicating the power profile information so that it can be changed during the lifetime of a flow based on the power situation.

An adaptive video application that changes the type and amount of video information sent was used to test the scheme. This experiment is based on work reported in [28]. Consider an MPEG-1 and MPEG-2 video stream with I (Intra), B (Bidirectional) and P

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[3] The queue length apparently drops from 10 to 0 because: (a) CBQ probes the queue length at finite intervals and all values are not recorded and (b) since TCP is used in Netperf, any drop in packet will trigger the sender to reduce the rate and the queue can drain quickly.

(Predictive) frames. In a low power situation we need to reduce the number of packets sent and the idea is to drop B frames first because this affects only the particular frame and the decoder can extrapolate the rest of the message. If the power level drops further then P frames can also be discarded with the B frames. I frames are discarded last. We used a simulated video stream which uses the ratio of I, P and B frames for two video rates of 1 Mbps and 384 Kbps as obtained from [41]. RSVP uses the source addresses and ports to classify flows. The various packets within a flow were identified by using different Type of Service (TOS) bits in the IP header for the various flows.

The aim of the experiment was to see the effect of reduced number of packets on the power level at the mobile. In other words, what is aimed at is to show that a flow with I, P and B packets consumes more power than a flow with only the I packets being sent. The power consumed at the mobile was measured using *apm* (advanced power management) [36] tool. The experiment did not produce a very definitive result because we do not currently have a tool to accurately measure the battery power consumption on a per-packet basis. The apm tool just reports the percentage of battery power left which is a very coarse measurement. Nevertheless, the architecture provides hooks to support power profile parameter should an application wish to use it. We are also currently looking at various mechanisms that can be adopted to put the WaveLAN card in sleep mode which consumes 15% of the power that is used in active receive mode [40]. The mechanism can be based on some prior agreement between the base station and the mobile about when the mobile can go into a sleep mode. This problem is harder when the mobile is receiving data since we have to know exactly when to turn the interface on and off. Improvements in power usage will be more dominant when the mobile is the sender of data in which case transmissions can be controlled.

Performance Feedback Factor

The aim of the experiment in this section is to show how the performance feedback factor works. Due to the high losses in the wireless networks, a receiver might not get the bandwidth it requested even though the sender has scheduled the requested amount. Therefore at some point, it might be necessary to compensate the user by allocating excess bandwidth than reserved for a certain period of time. The rate at which data is received is communicated by the receiver to the sender using the signaling mechanism. The sender compensates by allocating more bandwidth (if available). The experimental setup consists of a user program that sends data between the base station and the mobile. Fig. 9 records the the bandwidth used by the user application. Initially the user sends data at the rate of 0.22Mbps. At the instant denoted as (1) in the figure, feedback from the mobile indicates that there is need for some compensation to be provided for the class. The class is therefore provided extra bandwidth of about 0.2Mbps as shown between points (1) and (2) in the figure. The user reverts to its original bandwidth allocated after the compensation period.

Please note that the choice of a compensation mechanism is a complete study of its own [5,6] and beyond the scope of this paper. The experiment here just shows that the architecture provides support for such a mechanism. The amount of bandwidth to be compensated and the period of compensation were chosen arbitrarily in the experiment.

Probability of Seamless Communication

The testbed will follow a modified scheme from [11] to buffer packets at the old base station and forward it to a new base station. After a signoff message has arrived from the mobile (used in our handoff mechanism), the old base station buffers the packets till the routing has been set up to deliver the packets to the mobile in its new location. This will try and make the handoff as seamless as possible. This mechanism is currently under implementation.

To summarize the section, a set of experiments were designed to: (i) test the working of the passive reservation mechanism, (ii) test the working of various wireless network specific QoS parameters like loss profiles, power level, power profiles and performance feedback factor and, (iii) to evaluate the improvements made regarding RSVP control messages.

6. Conclusions and Discussions

This paper addressed the passive reservation scheme and the enhancement of RSVP (ReSerVation Protocol) to make it suitable for providing QoS assurances in wireless networks. Various characteristics of the wireless networks like high loss, low bandwidth, battery power constraints and mobility were considered in tailoring RSVP. The passive reservation mechanism helps reserve resources in a mobile environment. An experimental testbed was developed to test the feasibility of the proposed approach. Experimental results used to validate the enhancements include: (i) testing the passive reservation mechanism, (ii) showing the performance of the modified control message system and (iii) testing the working of the loss profiles, power level, power profiles and performance feedback mechanism. The handoff mechanism and the routing used in the system is also briefly discussed. More experiments are being done to validate the various aspects of this architecture, that will be reported in the future.

In all our discussions, we talked of resource reservations that have been made from the wired to the wireless networks. Reservations in the opposite direction (uplink) are also very important. For complete QoS guarantees in a mobile environment, the base station must be able to schedule the way in which it receives packets from the mobiles in addition to scheduling what is sent as discussed in this paper. This could be possibly done by some kind of polling or reservation-based mechanism. This is a topic for further study.

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Table 1
Performance of video stream with and without reservation

Setup	Time (secs)	Frames sent	fps
Only video traffic - Ideal situation	84.37	1074	12.73
Loaded condition: With reservation	105.85	1074	10.15
Loaded condition: No reservation			
Case 1:	Video Blocked		
Case 2:	Video Freezes		
Case 3:	121.75	1074	8.82

Table 2
Time for Reservation Setup Over Wireless Link.

Regular RSVP with losses	RSVP using consecutive messages with losses	Average Time without losses
29.62 secs	1.73 secs	0.017 secs

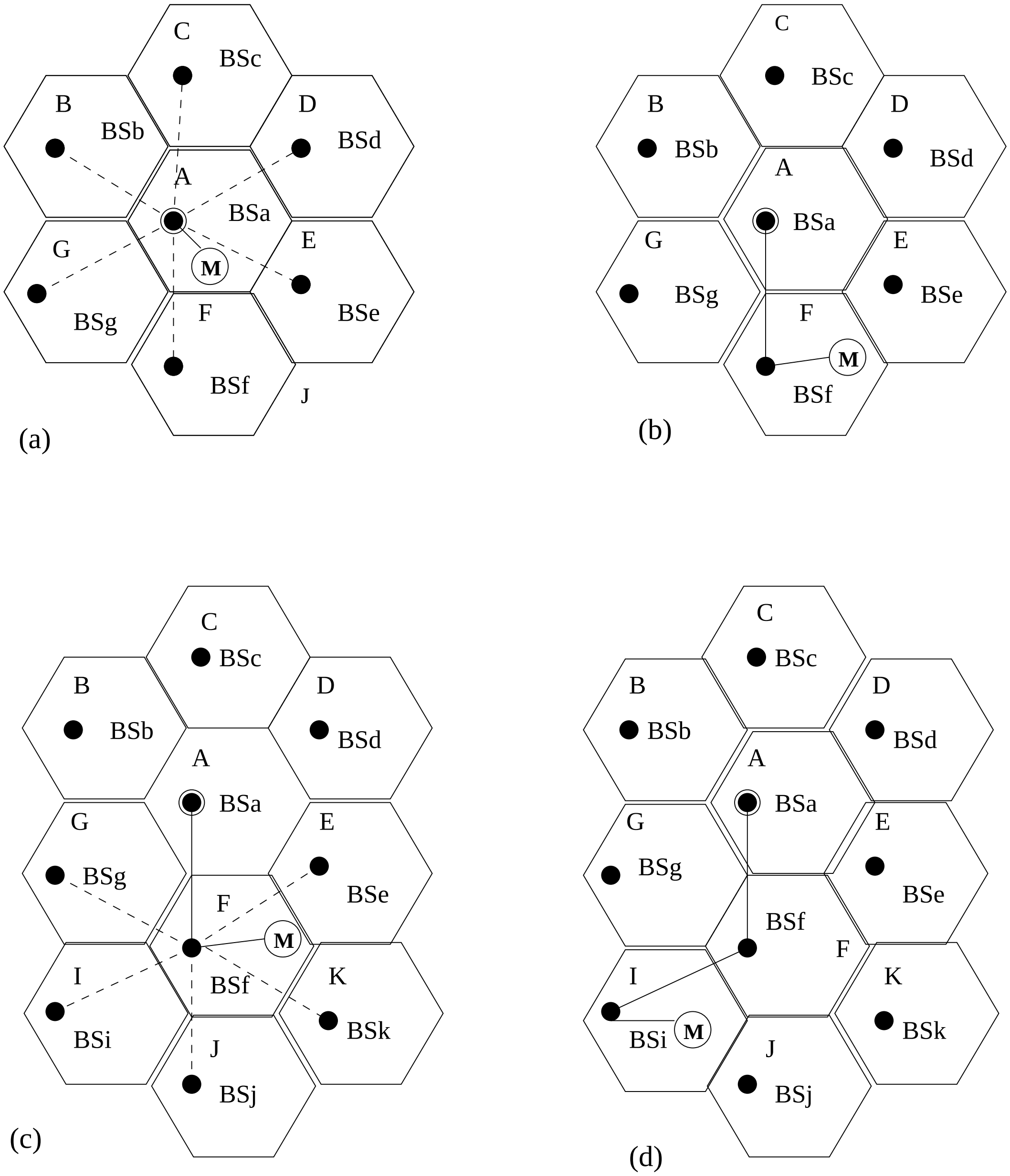

Figure 1. Overview of Passive Reservation Mechanism.

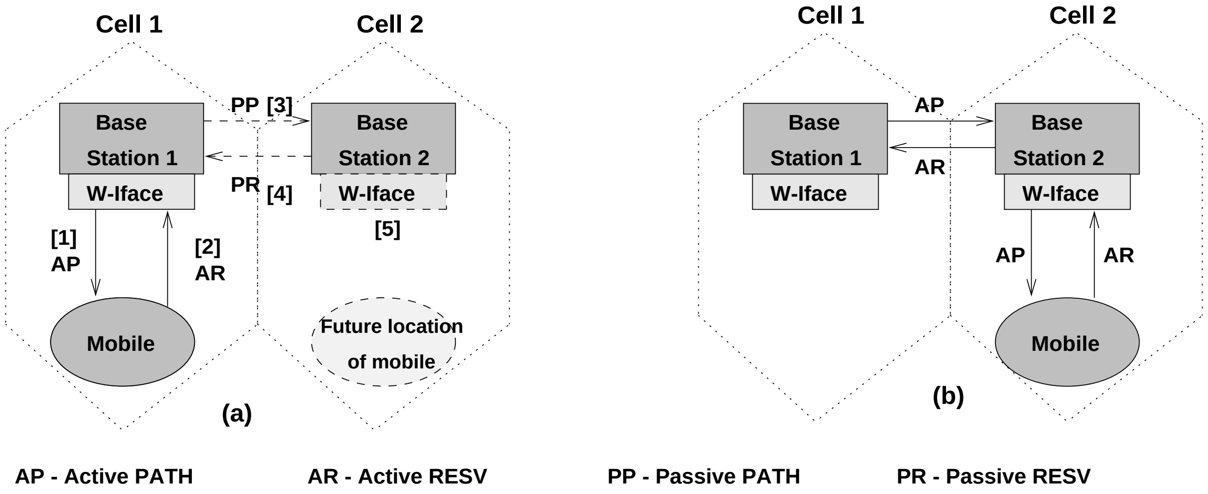

Figure 2. RSVP Messages for Reservation.

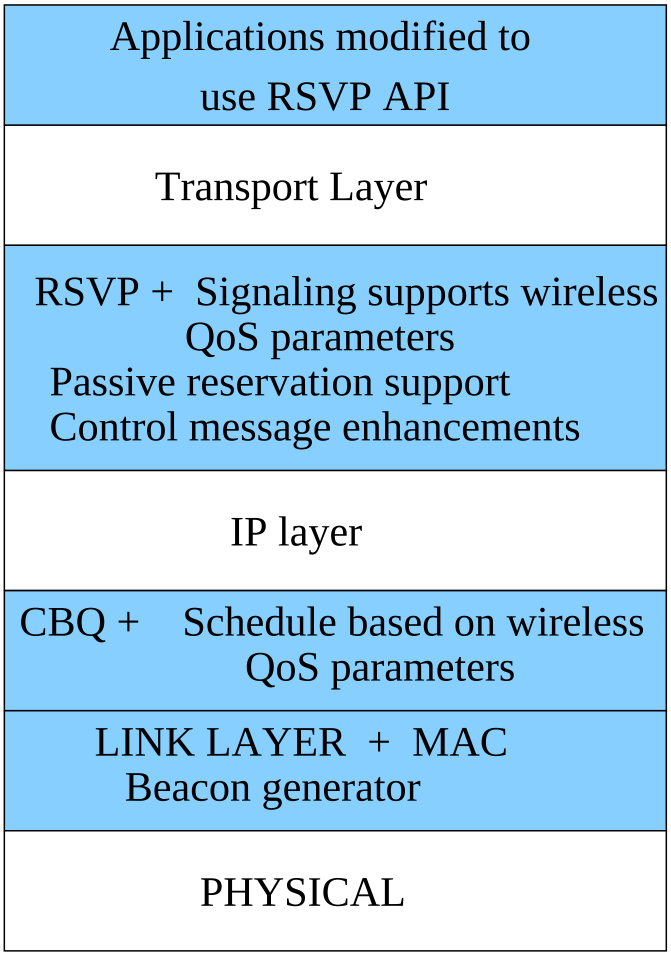

Figure 3. Modifications to Software at Various Protocol Layers.

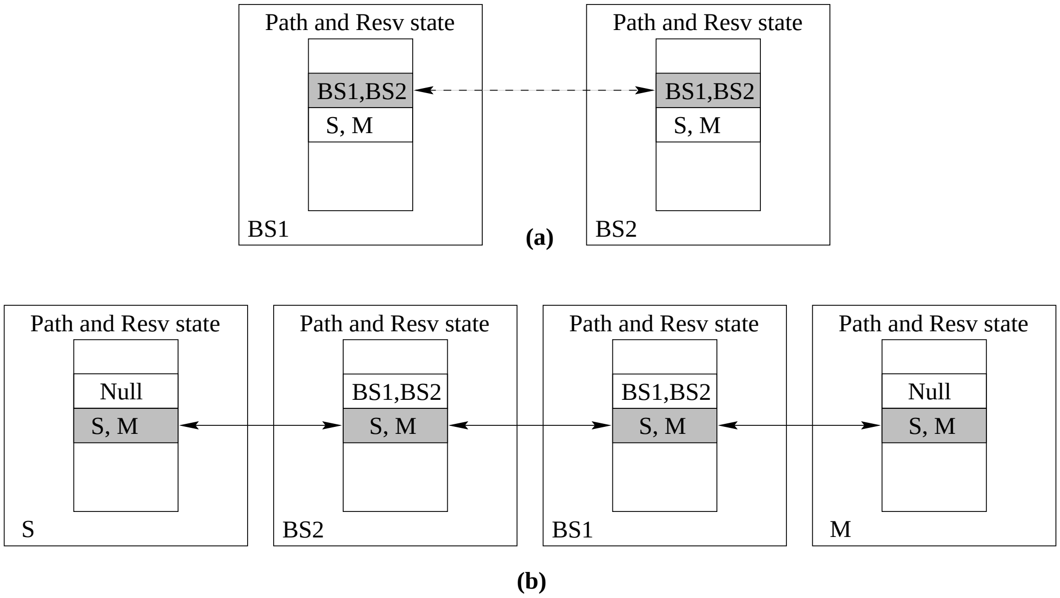

Figure 4. Addresses Used During Passive and Active Reservations.

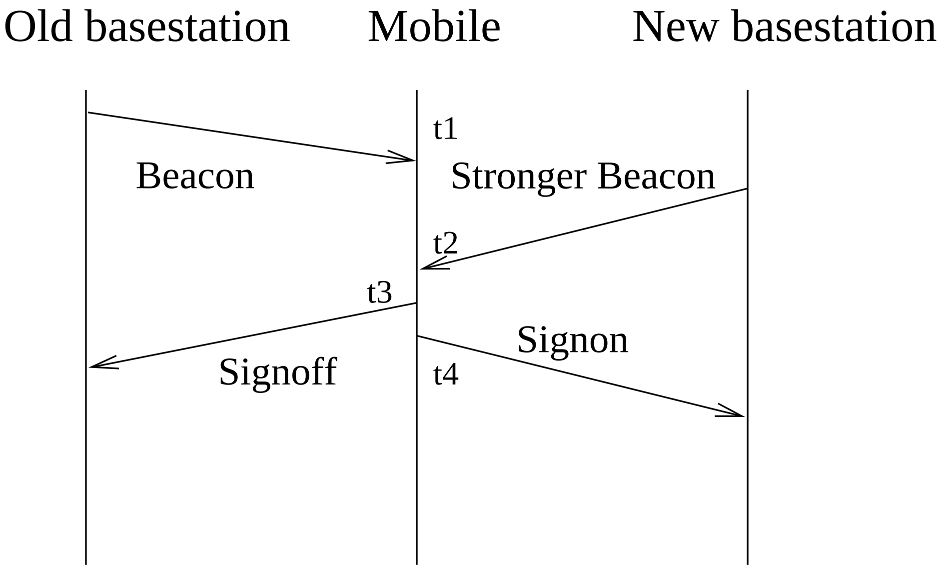

Figure 5. The Handoff Mechanism.

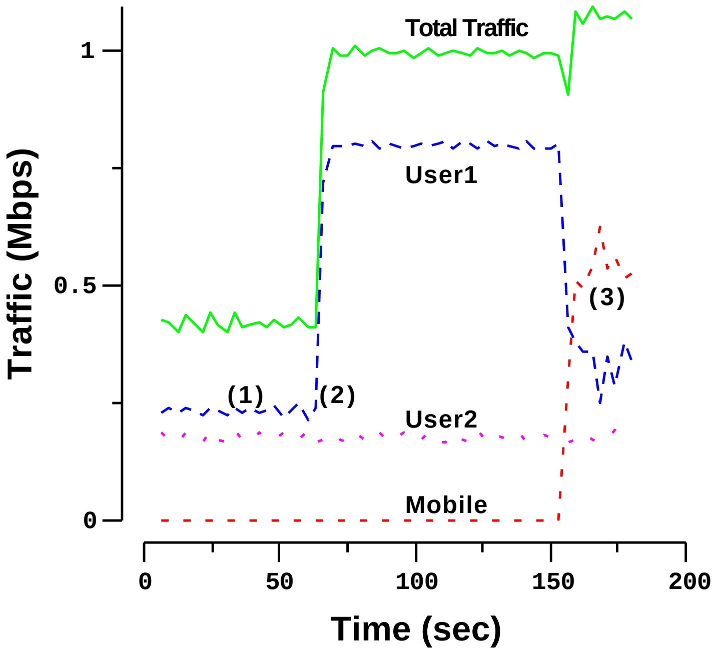

Figure 6. Usage of Passive Reservation.

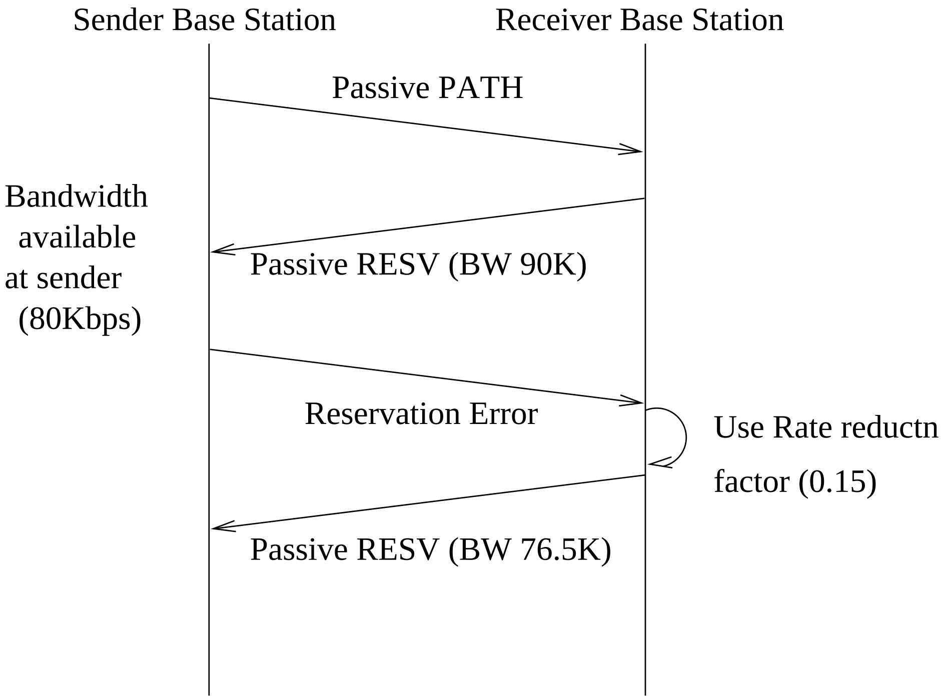

Figure 7. Mechanism of Rate Reduction Factor.

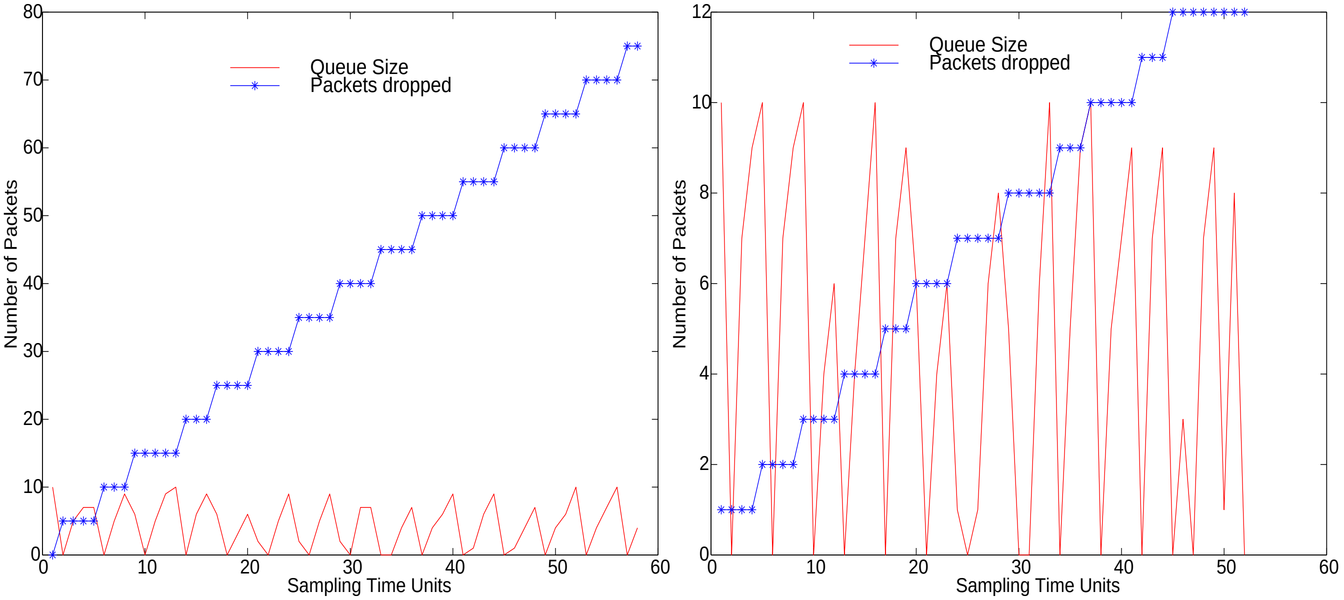

Figure 8. Bursty and Distributed Loss Based on Loss Profiles.

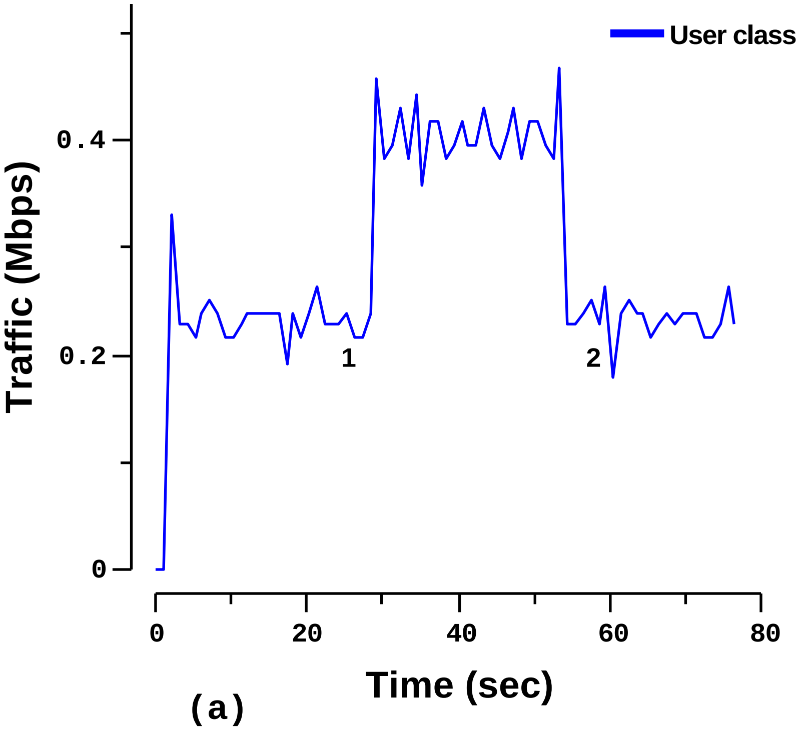

Figure 9. Compensation of Bandwidth.